Clinical applications of loudness scaling

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Fitting rules used in auditory rehabilitation usually have their main focus on detection thresholds. In state-of-the-art nonlinear hearing aids supra-threshold measures of the ear are also important and some of this information can be derived from loudness scaling. In three studies we examined the added value of loudness scaling for clinical applications. In a first study we performed loudness scaling in a group of musicians with primarily normal hearing. We measured loudness scaling with two narrowband (750 Hz and 3 kHz) and a broadband signal and investigated the relation with audiometric threshold. In a second study we examined the difference between monaural and binaural loudness perception in a subgroup of musicians. Finally we examined the correlations between self-reported problems and measures obtained from loudness scaling in a different group of hearing impaired employees. Our findings indicate that unaided loudness scaling may not be appropriate as a basis for prescription rules, but aided loudness scaling can be used successfully as a verification tool in the fine-tuning stage and to compare different outcomes.

INTRODUCTION

Fitting rules used in auditory rehabilitation are dominated by the thresholds and the uncomfortable loudness levels (UCL). Based on these two measurements the amount of gain and compression is selected. It would seem to be more appropriate to base the amount of gain and compression on a measurement of the complete shape of the loudness function rather than on a measurement of the extremes of the scale. However, measuring individual loudness functions is only interesting, when two conditions are fulfilled. First the accuracy of the loudness function must be good enough to obtain individual differences. Second a reliable reference function for normal hearing subjects must be available.

One possible measuring procedure to obtain the shape of the loudness function in a time-effective way, is the Adaptive CAtegorical LOudness Scaling (ACALOS) procedure (Brand *et al.*, 2002). In three large studies on auditory performance loudness scaling was obtained as part of the study. The parameters in each study varied according to the specific needs of the study. The loudness scaling results of these studies were analyzed to investigate

- The shape of the loudness function and its relation to auditory threshold
- The difference between monaural and binaural measurements
- The relation between the loudness function and listening effort

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SUBJECTS AND METHODS

In the first study 223 musicians from thee orchestras participated. The group was divided into 178 normal hearing and 45 hearing impaired subjects. Subjects were defined as hearing impaired if any threshold at the frequencies 500 Hz and 1, 2, 3 and 4 kHz exceeded 20 dB (HL). The major part of the subjects specified by this definition as being hearing impaired had a mild high frequency hearing loss.

All subjects of the first study performed ACALOS tests for three signals, narrowband noises at 750 Hz and 3 kHz and a broadband white noise. The signals were delivered by a loudspeaker at a distance of approximately 1 m.

In the second experiment a subgroup of 52 musicians performed ACALOS tests with TDH 39-headphones for monaural and binaural presentation at 1 kHz and 4 kHz (1/3 octave-band noises). For the binaural measurements the same signal was presented at both ears. The subgroup consisted out of 48 normal hearing subjects and 4 hearing impaired subjects according to the criteria described above.

In the last experiment a different group of 14 hearing impaired employees performed ACALOS tests at 750 Hz and 3 kHz and with a broadband white noise and they filled in a questionnaire on listening effort in silence and in noise. The signals were delivered by a loudspeaker at a distance of approximately 1 m. Six subjects performed the tests without hearing aids, the other eight subjects performed the tests with hearing aids, corresponding to their daily practice.

All measurements were conducted in a sound treated booth.

PROCEDURES

The loudness scaling procedure used was the Adaptive CAtegorical LOudness Scaling (ACALOS) procedure designed in Oldenburg by Brand and Hohmann (2002).This is a loudness scaling procedure with 11 response categories, 5 named categories, 4 unnamed intermediate categories, and 2 limiting categories, which correspond to categorical loudness levels from 0 to 50. The level assigned to a given loudness category x is termed the “categorical loudness level” Lx. An example of the response scale is given in Fig. 2. The procedure consists out of two phases. In the first phase the limits of the auditory range are estimated by an interleaved ascending and descending stimulus sequence. In the second phase the four named intermediate categorical loudness levels are estimated. This last phase consists out of two blocks. In the first block the four named intermediate categorical loudness levels are estimated by linear interpolation between the two limits of the auditory range, which are the values at L5 (very soft) and L50 (too loud). In the second block the named intermediate categorical loudness levels are estimated by a modified least-squares fit of a linear model function. In this study three iterations of the final block have been applied. The data is fitted with a model function consisting of two linear parts with independent slopes mlow and mhigh. The two parts are connected at 25 CU. The transition area between the loudness categories L_{15} and L_{35} is smoothed with a Bezier fit (Brand and Hohmann, 2002).

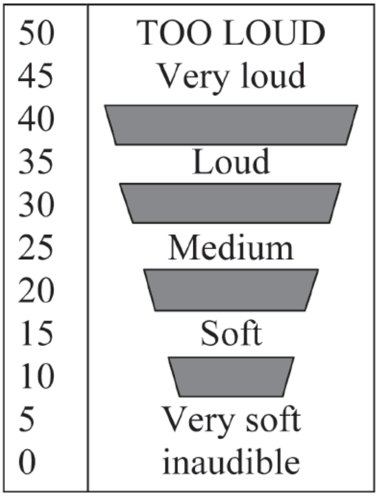

Fig. 1: Response scale, consisting of 11 response alternatives. The numbers on the left side indicate the categorical (units). They were not visible to the subjects during the tests.

RESULTS

Experiment 1: Loudness scaling in freefield

The data of the normal hearing and hearing impaired subjects were analysed separately. In Fig. 2 the mean fit and 5th and 95th percentile are presented for the normal hearing data. The spread in the data is large for all three signals. Correlations were calculated between the thresholds estimated with loudness scaling (CU5) and pure tone averages obtained from pure tone audiometry. No significant correlations were found for the normal hearing subjects. Correlations between CU5 and CU50 were also not significant. This means that for normal hearing subject no clear relationship exists between the audiometric thresholds and the thresholds obtained from loudness scaling. Apparently the accuracy of loudness scaling is not high enough at low levels to obtain an accurate threshold estimation in a rather homogenous group of normal-hearing subjects.

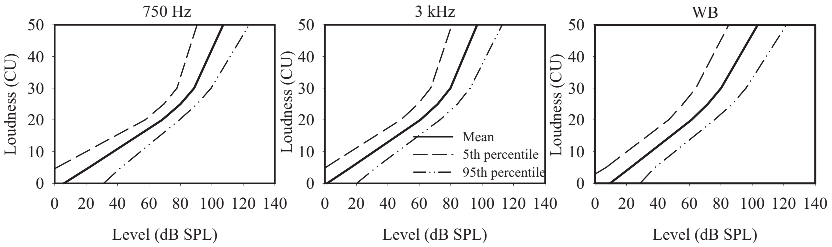

Fig. 2: Mean loudness functions for normal hearing subjects and the 5th and 95th percentile ranges for 1/3 octave bands around 750 and 3000 Hz and for a wideband noise.

Although, the figure for the hearing impaired subjects (not shown here) is very similar to Fig. 1, significant correlations were found ($p<0.05$) between CU5 values and pure tone averages. The correlations are shown in table 1. Again, no significant correlation between CU5 and CU50 values was found. The correlations are not very strong, but nevertheless they imply that in hearing impaired subjects loudness scaling is able to obtain threshold estimations. Note that the correlation between audiometric thresholds and estimated thresholds from loudness scaling is highest for 3 kHz. This is the frequency were the largest hearing loss is expected.

Audiometric threshold	Threshold ACALOS	Correlation
PTA0.5,1 kHz	CU5750Hz	0.549
PTA2,3,4 kHz	CU53kHz	0.647
PTA0.5,1,2,3,4,kHz	CU5WB	0.390

Table 1: Correlations between audiometric thresholds and thresholds obtained from loudness scaling (CU5) for hearing impaired subjects.

For the total group of normal hearing and hearing impaired subjects correlations were calculated between the dynamic range (DR) as defined by CU50-CU5 and m_{low} and m_{high}. Correlations are shown in table 2. All correlations were significant ($p<0.05$), but the correlations show that clearly the dynamic range is influenced stronger by the threshold than by the UCL.

m_{low}		
DR750Hz	-0.664	
	DR3kHz	-0.503
	DRWB	-0.652
m_{high}	DR750Hz	-0.498
	DR3kHz	-0.308
	DRWB	-0.358

Table 2: Correlations between lower and upper slopes of the loudness function and the dynamic range DR (CU50-CU5).

There was no significant correlation between mhigh and audiometric thresholds or CU5. This means that the high part of the loudness curve is independent from threshold.

Experiment 2: Loudness scaling with headphones

In Fig. 3 average loudness curves are shown for monaural and binaural measurements at 1 and 4 kHz.

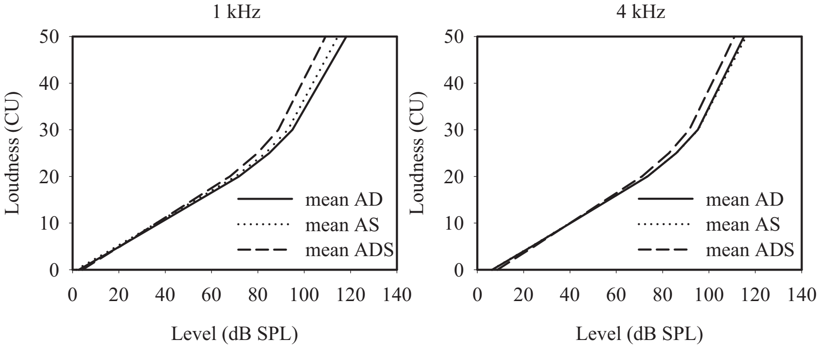

Fig. 3: average loudness functions for the right ear (AD), the left ear (AS) and binaural (ADS) stimulation at 1 kHz and 4 kHz.

The results show for higher levels, that binaural signals presented at equal levels are perceived louder than monaural signals. This effect is somewhat stronger at 1 kHz than at 4 kHz. A paired T-test shows significant differences in level between monaural and binaural measurements for CU20, CU25, CU30 and CU50, but not for CU5, both at 1 kHz and at 4 kHz. Level differences between measurements at the right and left ear were not significant for 4 kHz and 1 kHz except for CU25 and CU30 at 1 kHz.

Experiment 3: Loudness scaling aided and unaided

In this experiment the outcome of a questionnaire on loudness effort was correlated with measures obtained from loudness scaling. The questionnaire consisted out of four possible answers; ‘no effort’, ‘little effort’, ‘moderate effort’ and ‘high effort’. Several measures were correlated with the outcome of the questionnaires. The highest correlations were obtained with the ratio m_{high}/m_{low}. This ratio is one if the loudness curve is linear, larger than one if the loudness curve is concave and lower than one if the curve is convex. Fig. 4 shows the effort of listening in noise against the ratio m_{low}/m_{high}.

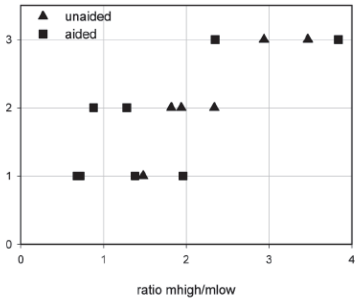

Fig. 4: Listening effort in noise as a function of the ratio mhigh/mlow. The numbers correspond to: 0 “no effort”, 1 “little effort”, 2 ”moderate effort” and 3 “high effort”.

The results suggest that very concave loudness functions increase listening effort in noise both in unaided and aided loudness scaling.

DISCUSSION AND CONCLUSIONS

In the studies described above we measured loudness scaling for normal hearing subjects and hearing impaired subjects, in freefield and with headphones, and aided and unaided. In all studies we evaluated the extra information contributed by loudness scaling.

The results of the first study show that it is hard to define one single normal loudness function. The spread in loudness functions within the normal hearing subjects is too large. The correlations between audiometric thresholds and the thresholds from loudness scaling are also too weak. The correlations between audiometric thresholds and thresholds from loudness scaling improve if a hearing loss is present. This is a logical consequence from the steepening of the loudness function at low levels in hearing impaired subjects, which leads to a more accurate threshold estimation in the loudness scaling data.

Brand and Hohmann (2002) already reported that some normal-hearing listeners reported that they were forced to respond less accurate than they could, especially at low levels. In other studies performed in our lab, normal hearing subjects reported the same problem. The inability to make an accurate judgement may have led to less accurate threshold estimates in the loudness scaling. Because of the steeper loudness growth in hearing impaired listeners, the problem of shortage of response options at low levels is not present. The authors are not aware of any studies in which threshold estimates of loudness scaling and standard audiometry are compared as done in this study.

The group results lead to another interesting finding. Hearing loss in this population mainly influences the lower part of the loudness function. The higher part of the loudness function is independent from both audiometric thresholds and thresholds obtained from loudness scaling. The results in this study strongly suggest that recruitment is limited to low and medium levels. The upper parts of the loudness curve show no consistent steepening with increasing threshold and therefore no recruitment. This suggests that for normalization of loudness, compression should be applied mainly for the lower levels with linear amplification at high levels, as otherwise the shape of the normal loudness function will be distorted.

The results of the second study show a clear difference between monaural and binaural loudness measurements. Binaurally presented signals are clearly perceived louder than monaurally presented signals. It is interesting to see that this effect mainly occurs at the higher levels. At low levels no binaural summation was found. This is in line with a few other studies that show more binaural loudness summation at high levels than at low levels (Reynolds and Stevens, 1960; Scharf and Fishken, 1970; Whilby *et al.,* 2006; Zwicker and Zwicker, 1991). However data from for instance Marks (1978) do not show an influence of level. The binaural loudness data may have implications for hearing aid fitting. In hearing aid fitting loudness normalization is often one of the main targets. However hearing aid fittings are normally evaluated monaurally and not binaurally. If binaural loudness summation is indeed level dependent this should be taken in consideration in the hearing aid fitting.

The final study was done in a very heterogeneous group of subjects. Therefore no strong conclusions may be drawn from this study. The fact that the relationship between linearity of the loudness function and listening effort in noise also appears in the unaided measurements, shows at least that the effect is not created by inadequate hearing aid fitting. On the other hand if the relationship between high listening effort and very concave loudness functions can be confirmed in follow-up studies, this knowledge may have important consequences for hearing aid fitting. In that case extremely concave loudness functions should be avoided. This means that the use of strong compression needs some precautions.

In conclusion, these studies show that loudness scaling can give us more insight in loudness scaling on group level. The normal spread in loudness functions is too large to make any fair comments on individual loudness functions in comparison to the average curve for normal hearing listeners. Comparison of loudness functions of the same subject for different conditions may however be very useful.

REFERENCES

Brand, T., and Hohmann, V. (**2002**). “An adaptive procedure for categorical loudness scaling,” J. Acoust. Soc. Am. **112**, 1597-1604.

Marks, L. E. (**1978**). “Binaural summation of the loudness of pure tones,” J. Acoust. Soc. Am. **64**, 107-113.

Reynolds, G. S., and Stevens, S. S. (**1970**). “Binaural summation of loudness,” J. Acoust. Soc. Am. **32**, 1337-1344.

Scharf, B., and Fishken, D. (**1970**). “Binaural summation of loudness reconsidered,” J. Acoust. Soc. Am. **86**, 374-379.

Whilby, S., Florentine, M., Wagner, E., and Marozeau, J. (**2006**). “Monaural and binaural loudness of 5- and 200-ms tones in normal and impaired hearing,” J. Acoust. Soc. Am. **119**, 3931-3939.

Zwicker, E., and Zwicker, E. T. (**1991**).“Dependence of binaural loudness summation on interaural level differences, spectral distributions, and temporal distributions,” J. Acoust. Soc. Am. **89**, 756-764.